

On atomic structure of Ge huts growing on the Ge/Si(001) wetting layer

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Abstract

Structural models of growing Ge hut clusters—pyramids and wedges—are proposed on the basis of data of recent STM investigations of nucleation and growth of Ge huts on the Si(001) surface in the process of molecular beam epitaxy. It is shown that extension of a hut base along $\langle 110 \rangle$ directions goes non-uniformly during the cluster growth regardless of its shape. Growing pyramids, starting from the second monolayer, pass through cyclic formation of slightly asymmetrical and symmetrical clusters, with symmetrical ones appearing after addition of every fourth terrace. We suppose that only symmetrical configurations of pyramids composed by 2, 6, 10, 14, etc. terraces over the wetting layer are stable. This might explain less stability of pyramids in comparison with wedges in dense arrays obtained at low Ge deposition temperatures. Possible nucleation processes of pyramids and wedges on wetting layer patches from identical embryos composed by 8 dimers through formation of 1 monolayer high 16-dimer nuclei different only in their symmetry is discussed. Schematics of these processes are presented for both species of huts.

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I. INTRODUCTION

Ge “hut” clusters or small self-assembled Ge/Si(001) clusters faceted by the $\{105\}$ planes and coherent with the substrate lattice (pyramids with square bases and wedges with rectangular bases elongated in one of the $\langle 100 \rangle$ directions),^{1–4} which form on the Ge wetting layer (WL) at low temperatures of Si substrates ($\lesssim 600^\circ\text{C}$) in the process of ultrahigh-vacuum molecular-beam epitaxy (UHV MBE) or—probably with some peculiarities due to hydrogenation of WL—in the process of chemical vapor deposition, have attracted an interest of researchers for more than twenty years since their discovery by Mo *et al.* in 1990¹, because of both their potential practical importance for development of Si-based monolithic optoelectronic devices^{5,6} and convenience and simplicity of their usage as model objects for investigation of the Stranski-Krastanow growth of heteroepitaxial structures.

A lot of articles published during these years were devoted to a complicated issue of hut appearance and its further growth on the WL (see, e. g., Refs. 4, 7–15 and numerous articles cited therein). However, only a few of these works studied this issue on atomic level.^{14–18} Investigations carried out on atomic-level were mainly devoted to the structure of the $\{105\}$ facets for which an initially proposed simple model based on paired dimers¹ (the so called PD model) was eventually replaced by a model considering step rebonding as a source of the facet stability¹⁹ (the latter one is usually referred to as the RS model) rather than to exploration of cluster nucleation or its in-height or longitudinal growth.

Our recent experimental explorations^{6,14–18,20} carried out on atomic level by high-resolution STM have demonstrated fine details of hut nucleation and its evolution during the growth which however have not been sufficiently interpreted thus far and presented in terms of structural schematics and drawings which would be helpful for further theoretical calculations and numerical simulations. For example, we have discovered the phenomenon of simultaneous appearance of two types of nuclei^{14,18} which are composed by 16 dimers and different only in symmetry—a separate nucleus for each species of huts—on tops of Ge WL $M \times N$ patches of 4-monolayer¹⁷ (ML) height (Fig. 1). Unfortunately, no satisfactory explanation of this phenomenon has been proposed thus far which would describe a driving force of this strange behaviour of Ge dimers which group in two different formations, instead of a single one, to relieve the rising mechanical stress in WL patches.^{17,18}

We have demonstrated that both pyramids and wedges grow in height conserving the

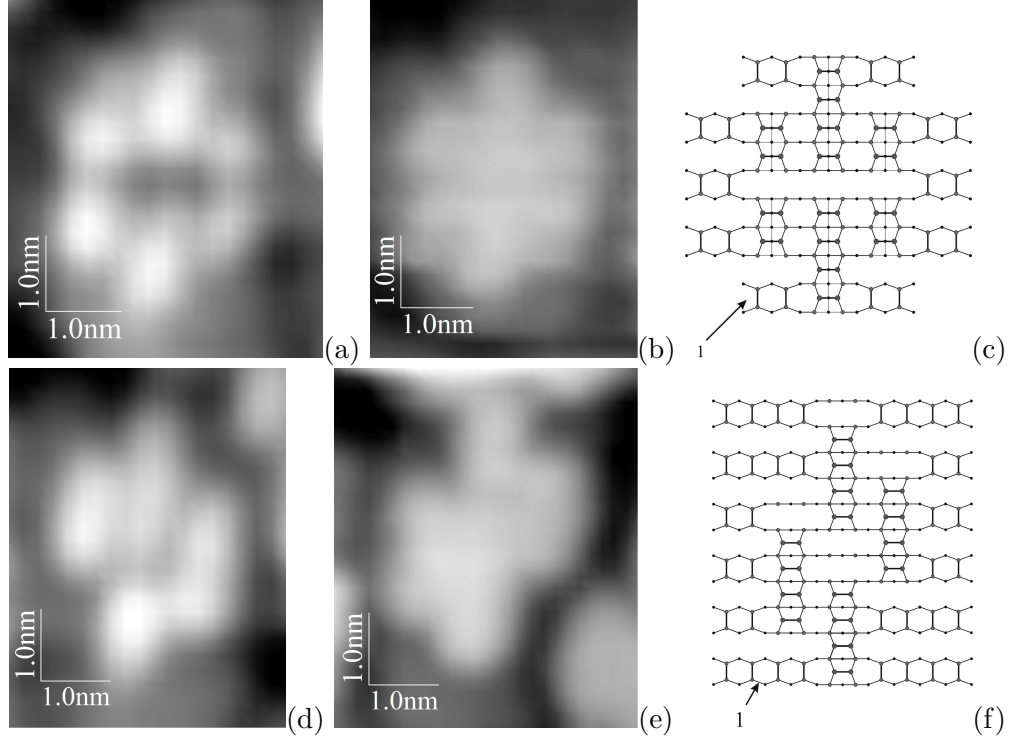


FIG. 1. STM empty state images of Ge hut nuclei on patches of Ge/Si(001) wetting layer and their schematic representation as 16-dimer structures of different symmetry: pyramid nuclei (a, b) and a sketch of their atomic structure (c); wedge nuclei (d, e) and their structure (f);¹⁴ figure ‘1’ designates dimer rows of the top layer of a wetting layer patch.

width and the atomic structure of their apexes (the topmost (001) terraces).^{4,6,16} This phenomenon also requires comprehension and adequate description: up to date, we have only hinted at such description in our recent articles.^{14–16}

An aim of this article is to propose physical processes on WL and cluster facets, and their structural schemes, on the basis of the previously performed STM studies, which could give adequate interpretation on atomic level to the experimentally observed evolution of each species of hut clusters during their growth setting the direction of thought for explanation of the presently incomprehensible phenomenon of simultaneous appearance of two types of hut nuclei on Ge/Si(001) WL which give rise to two mutually independent species of huts.^{4,14}

II. EXPERIMENTAL

A. Techniques

Experiments were carried out using a specially built setup^{15,16} consisting of a UHV MBE vessel (Riber EVA 32) connected with a UHV STM chamber (GPI 300)²¹. Details of the pre-growth treatments of Si wafers, which included chemical etching and oxide removal by short high-temperature annealing ($T \sim 900^\circ\text{C}$), can be found in our previous articles cited in Refs. 22 and 23. Thin films of Ge were deposited directly on the clean Si(001) surface, purified from the oxide,²³ at the temperatures of 360, 530, 600 or 650°C . Parameters of Ge deposition processes as well as results of our structural explorations of Ge huts and wetting layer performed by high-resolution UHV STM are presented in detail, e.g., in Refs. 4, 6, 14–18, and 20. The WSxM software was used for processing of STM images.²⁴

B. Summary of Main Results

Beginning the presentation of ideas and conclusions, which are in the focus of the current article, we would like to outline for the readers the main experimental observations and models on which our further consideration is based.

As mentioned above, at the growth temperatures below 600°C formation of two species of Ge hut clusters—ones with square bases or pyramids and ones with rectangular bases elongated in one of the $\langle 100 \rangle$ directions or wedges—is observed on WL.^{1,4,10,14,25} Our STM data demonstrate these two cluster forms to grow from different types of nuclei which have different structures and symmetries.^{14,17} Fig. 1 presents STM images of these nuclei and models of arrangement of their atoms on WL. Exploration of apex structure of bigger huts has shown that it is also different for pyramids and wedges.^{4,14} Both nuclei reconstruct WL patch tops on which they appear (each on a single patch). Nuclei of pyramids transform to 3-D huts without any further reconstruction; a growing pyramid always reproduces a blossom-like shape of the nucleus on its vertex keeping its apex unchanged (Fig. 2 a, b).¹⁴ Nuclei of wedges are being reconstructed when the second layer of a cluster forms (Fig. 2 c, d);^{4,14} as a result of this shape transition a formation arises which then is repeated as a basic unit in the structure of a ridge of a wedge-like cluster of any height and width (Fig. 2 d, e). So, the width of apexes of wedges of any height and width is also permanent.^{4,14} Meanwhile,

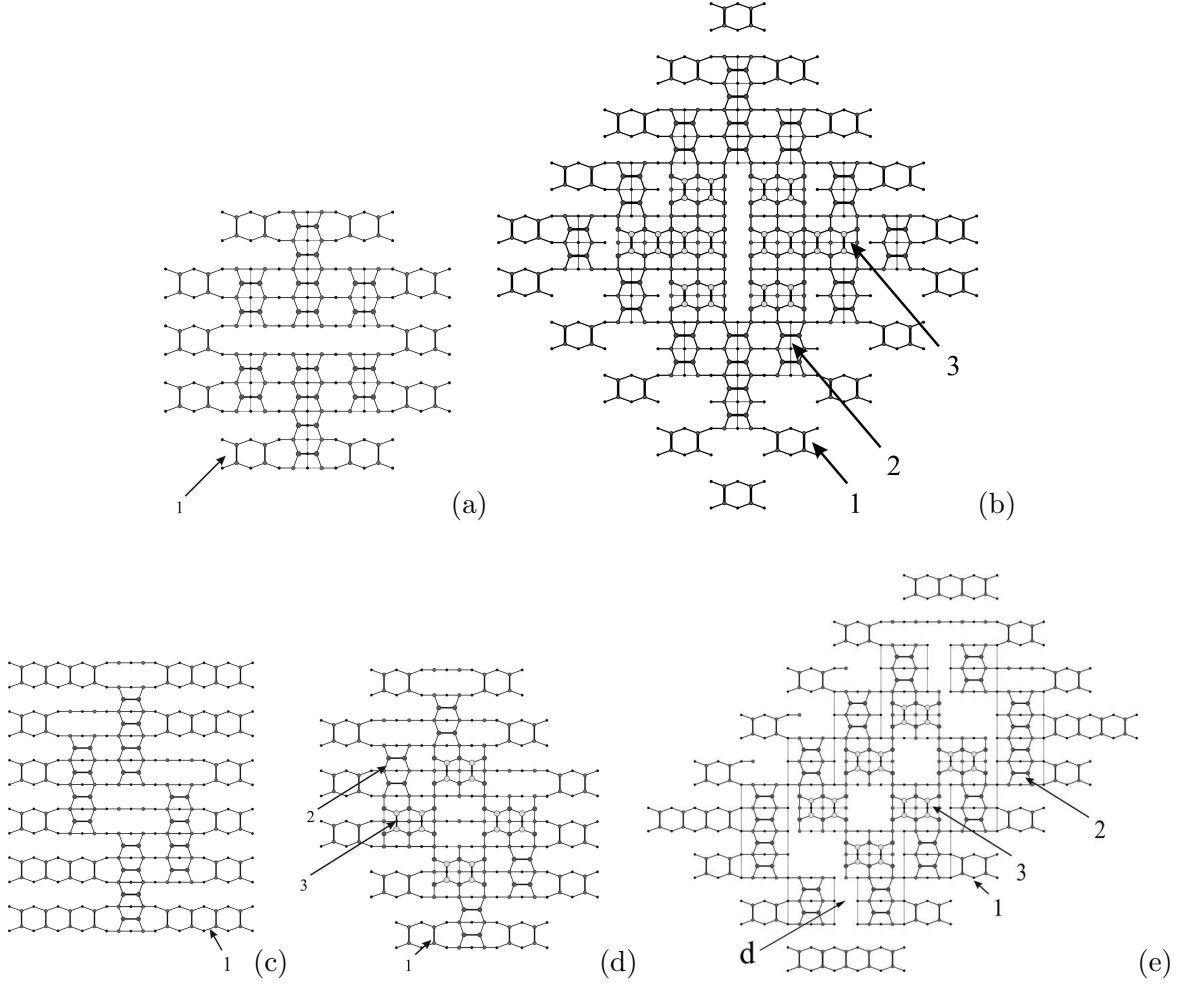


FIG. 2. Schematics of hut nucleation: a nucleus of a pyramid arising reconstructs the surface a WL patch (a) and then transforms into a 2-ML pyramid (b) which repeats the nucleus structure on its apex; a nucleus of a wedge also reconstructs the WL patch surface (c) and the second layer reconstructs the nucleus to form a correct structure of its apex (d); a 2-ML wedge repeats this structure on its ridge (e); when a wedge takes the right shape, point defects arise on its opposite triangular $\{105\}$ facets (the defect is shown by the letter ‘d’ on one of the triangular facets) and determine the axis for its elongation;¹⁴ figures ‘1’, ‘2’ and ‘3’ indicate WL, first and second terraces of the clusters, respectively.

point defects form at the penultimate terrace of both triangular facets of a wedge because of the ambiguity of locations of the dimer pairs near the gap indicated by the letter ‘d’ in Fig. 2 e; this pair of defects on the opposite sides of a cluster likely determines the axes along which the cluster can then elongate; probably these defects is a reason of the longitudinal

growth of wedges^{14,15} resulting to formation of very long huts⁴ and even quantum wires of enormous²⁶ aspect ratios. Notice, that pyramids do not contain such defects on any pair of their opposite triangular facets and, probably, this is the reason that they cannot elongate. This is one of the most important structural differences of pyramids and wedges which likely determines the difference in the processes of their growth.

It has been known also since the pioneering works^{1,2} that facets of huts are $\{105\}$ planes formed by (001) terraces separated by monoatomic steps and that clusters grow in height due to formation of new (001) terraces. Our recent works^{14,15,20} have presented additional data of an accurate STM study of the hut facet structure. The obtained STM micrographs of the $\{105\}$ facets of huts have been shown to correspond to the PD model¹ rather than the RS¹⁹ one, and a conclusion has been made that $\{105\}$ facets of hut consist of non-rebonded (001) terraces;²⁰ the same conclusion has been made from a simple crystallographic consideration of nucleating huts (Fig. 2).^{14,15} The width of (001) terraces on the $\{105\}$ facets has been found to be equal to 2 translations of the crystalline lattice in the $\langle 110 \rangle$ direction.

A commonly adopted opinion related to occurrence of wedges (elongated huts) is that they arise due to elongation of pyramids in one of two equivalent $\langle 100 \rangle$ directions;^{7,8,27} an issue of preferential growth on one (or on two opposite) of four energetically degenerate facets is quite unclear though.⁴ According to the data of our STM studies such transition is impossible, a pyramidal hut cannot change its symmetry and transform into wedge-like one (and vice versa) because apexes of these clusters, as well as their nuclei, have different structures.^{4,14,15}

III. HUT GROWTH AND APPEARANCE: MODELS AND PROCESSES

Now, being aware of the necessary empirical facts, we can proceed with consideration of atomic models of processes which explain them.

A. Models of uniform and non-uniform growth

Figures 3 to 7 schematically present atomic models of the in-height growth of hut-clusters drawn on the basis of the above experimental data. There are two possible models of processes which, in principal, may describe the growth of huts.¹⁶ The first one implies that

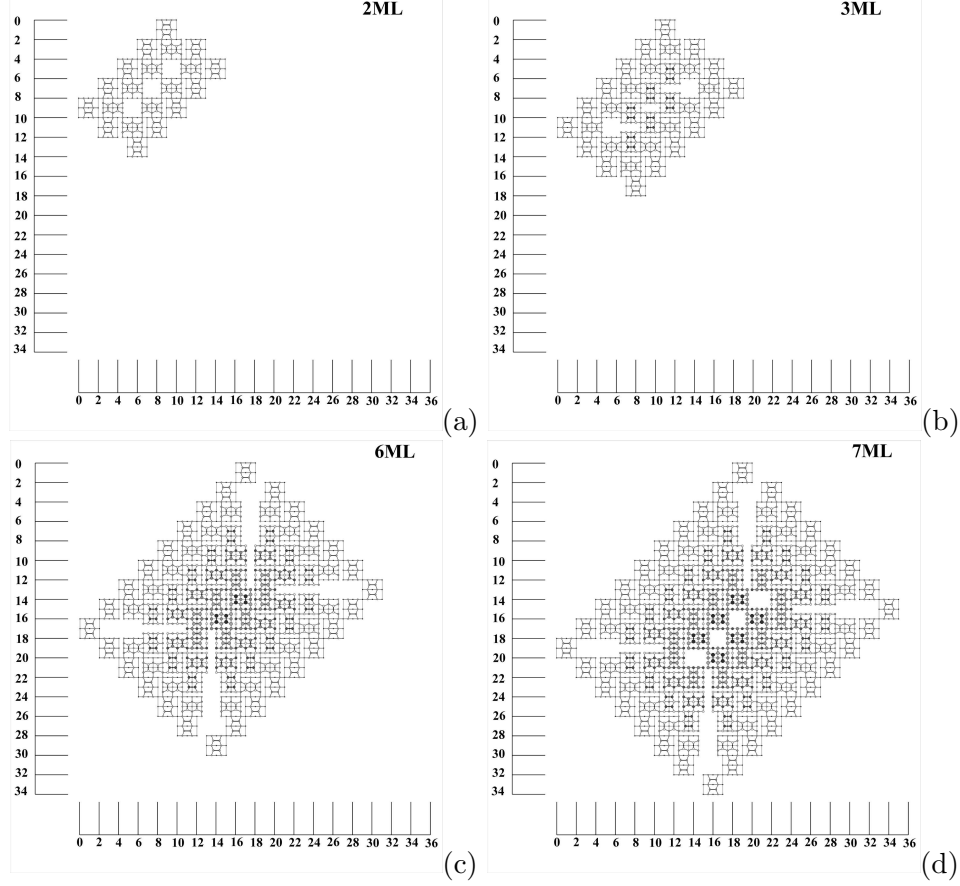


FIG. 3. A model of uniform growth of a wedge-like hut: the cluster effective height over WL is 2 (a), 3 (b), 6 (c) and 7 (d) ML; the real height of the latter hut is only 6 ML over WL but its width corresponds to 7 ML. Only the structures of the $\{105\}$ facets and apexes are shown. The scales show the cluster base widths along the $\langle 110 \rangle$ axes expressed as a number of elementary translations.

the cluster growth goes on due to uniform attachment of Ge atoms to all cluster facets (we refer to this model as *a model of uniform growth*).¹⁶ This means that the width of a cluster in all $\langle 110 \rangle$ directions increases by the value of two elementary translations (or in total by four translations along each $\langle 110 \rangle$ axis; as Ge WL is compressed and its lattice corresponds to the Si one, the elementary translation in this direction is 3.84 \AA) after each step of completion of the cluster facets (Fig. 3). For the simplicity of presentation we do not show the structure of hut edges which is not essential for understanding; we do not consider elongation of wedges along $\langle 100 \rangle$ axes (the longitudinal growth) either. For the mechanism of uniform growth the structure of a wedge-like hut ridge would depend on the

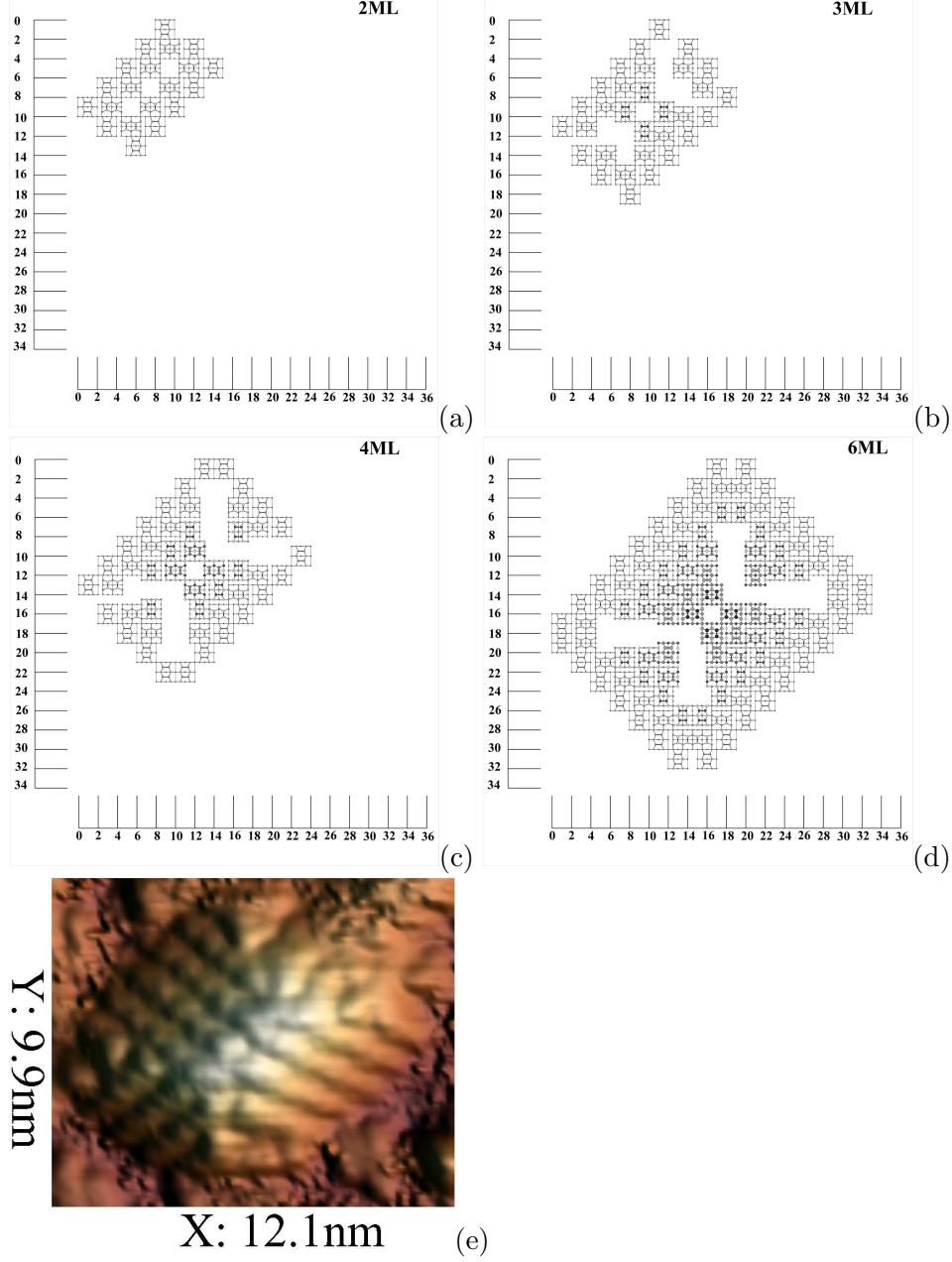


FIG. 4. (Color online) A model of non-uniform growth of a wedge-like hut: the number of completed layers over WL is 2 (a), 3 (b), 4 (c) and 6 (d). Only the structures of the $\{105\}$ facets and a unit cell of the apexes are shown. The abscissa and ordinate axes show the cluster base widths along the $\langle 110 \rangle$ axes expressed as a number of elementary translations. An STM micrograph of a wedge (4ML high over WL) is given as an example demonstrating the apex structure [Ge deposition temperature is 360°C, Ge coverage is 5.4 AA, bias voltage is +1.8 V, tunneling current is 100 pA].

cluster height²⁸ (Fig. 3); the dimer arrangement on the apexes would be analogous for the wedge heights of 2 ML and of 6 ML with the base width corresponding to 7 ML which is shown in Fig. 3d under the designation of 7 ML because it would form as a result of 7 rounds of completion of its facets. In other words, the ridge structure of the 2-ML wedge would be reproduced after completion of every next 5 ML during the cluster growth. In Fig. 3, the cluster height of 2 ML is chosen as an initial point; the 3-ML cluster is obtained as a result of widening of the base by 2 translations in each of the $\langle 110 \rangle$ directions. The ridge structures of the 2-ML and 3-ML clusters do not coincide. Further expansion of the cluster is similar. The 6-ML cluster (Fig. 3c) would have a simple top structure demonstrating *observable ridge narrowing*. After completion of 7 layers the cluster apex would repeat the structure of the 2-ML wedge but the cluster real height would be only 6 ML over WL, i.e. being 6 ML in height it would have the base area corresponding to the height of 7 ML. According to our observations^{4,15,16} made by STM and to the data obtained by different authors and presented, e.g., in Refs. 2, 3, and 19 wedge-like huts of different heights always have the same structure of ridges (which is clearly seen in Fig. 4e). So, we can conclude that the above model of uniform growth of wedges finds no confirmation by experimental data in the case of Ge huts.

The other model implies that huts grow due to non-uniform attachment of Ge atoms to each of the $\{105\}$ facets (we refer to this model as *a model of non-uniform growth*);¹⁶ this means that the cluster width in each of the $\langle 110 \rangle$ directions increases by two or three translations when the cluster height rises by 1 ML. Such process of growth ensures the independence of atom arrangement on the hut apex of the cluster height, as observed in experiments. This model for the case of wedge-like huts is illustrated by Fig. 4. The direction in which the wedge base expands to 3 translations changes with the increase in the cluster height by 1 ML because this direction is determined by the direction along which the rows run forming the topmost (001) terrace. This is schematically presented in Fig. 5. Arrows in the drawing show the $\langle 110 \rangle$ directions along which Ge atoms attach to the corresponding facet; the figures next to the arrows display a number of translations to which the facet shifts in this direction. The hut cluster is represented by the rectangle divided to two sections by the diagonal. On one side from the diagonal the cluster base expands to two translations in each of the indicated $\langle 110 \rangle$ directions; on the other side the growth process is more complicated. The direction of the base expansion to three translations is

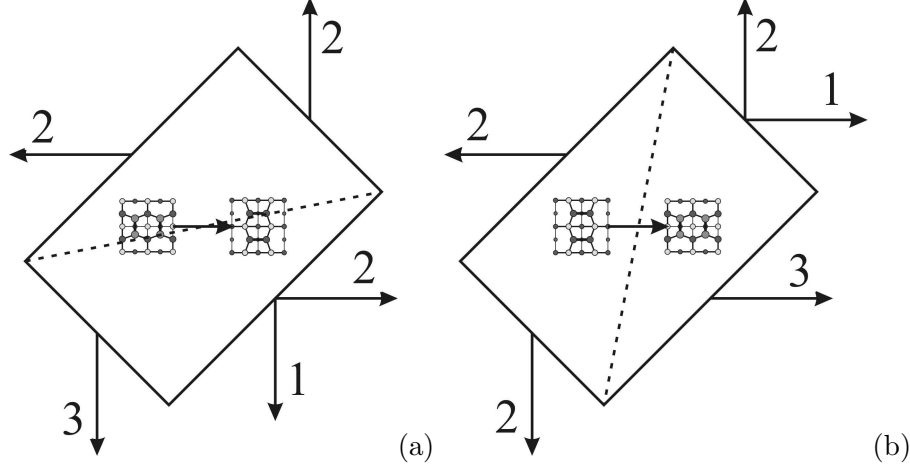


FIG. 5. Schematic representation of non-uniform growth by 1 ML of a wedge-like hut-cluster depending on the initial and final direction of dimer rows on its apex: the apex transformation is shown by sketches of atomic configurations of the unit cells connected by arrows on the diagonals of the rectangles; the arrowheads show the final directions. Arrows at bases show the $\langle 110 \rangle$ directions and figures near them designate a number of elementary translations by which the corresponding base side is shifted in each direction due to the increase in the cluster height by 1 ML.

determined as follows (Fig. 5): If a cluster, which originally had, e. g., horizontally oriented rows on its ridge (Fig. 5 a), increases its height by 1 ML and its apex rows become vertically oriented (Fig. 5 a) then a direction of its base expansion to three translations coincides with the resultant direction of dimer rows on its top. The adjacent facet situated on the same side of the cluster with respect to the diagonal also grows following a more complex rule than the facets situated on the opposite side: its base expands in two directions at once but to different number of elementary translations—expansion to one translation goes on in the resultant direction of the dimer rows on the ridge whereas a direction of the base side shift by two translations coincide with the initial direction of rows on the cluster top (Fig. 5 a). The analogous process for the next step of completion of the cluster facets and cluster growth by the next 1 ML is presented in Fig. 5 b.

Fig. 6 demonstrates schematics of growth of pyramidal clusters. According the STM observations atom configuration on pyramid vertices does not depend on the cluster height and coincide with that in the pyramid nucleus^{4,14,15} so, like in the former case, the process the pyramid growth corresponds with the model of non-uniform growth. Fig. 7 illustrates this process. During the pyramid growth by 1 ML its base sides move either by two or by

three translations in the directions shown by arrows in Fig. 7. The direction of the base expansion to three translations is determined as follows (Fig. 7 a): as contrast to the case of the wedge-like cluster, this direction is normal to the final direction of dimer rows on the cluster vertex; two facet bases on one side from the diagonal (which is shown by the dashed line in Fig. 7 a) move by three translations in the indicated direction whereas the rest two facet bases situated on the other side from the diagonal are shifted by only two translations in the opposite direction. Let us consider the initial phase of the pyramid growth depicted in Fig. 6. A diagram shown in Fig. 7 a corresponds to the transition from 2 ML to 3 ML in the pyramid height (Fig. 6 a, b); as a result of this step a symmetrical 2-ML pyramid transforms into slightly asymmetrical 3-ML one because of the process of non-uniform growth. The next transition between 3 and 4 ML (Fig. 6 b, c) happens in accordance with the process plotted in Fig. 7 b which also results in formation of a slightly asymmetrical 4-ML pyramid with the apex structure rotated 90° with respect to the previous one; the process diagram is also seen to be rotated 90° clockwise. The next rotation of 90° clockwise of the cluster expansion process (Fig. 7 c), corresponding to the next step of completion of the cluster facets, forms a 5-ML pyramid with the tiny violation of its symmetry (Fig. 6 c, d). And finally, a symmetrical 6-ML high pyramid forms (Fig. 6 d, e) as a result of the step schematically drawn in Fig. 7 d which is again rotated 90° clockwise; this cluster restores the symmetry of the 2-ML one. (Notice that all the above mentioned violations of the pyramid symmetry result in difference in the length of base diagonals of only 1 elementary translation.) Afterwards the cycle repeats resulting in formation of higher pyramids. (STM micrographs of 3 and 5-ML pyramids illustrate this model in Fig. 8).

Thus, a cycle of four consecutive steps (processes) of the pyramid expansion (completion), each rotating 90° with respect to the previous one, and all rotating in the same direction—clockwise or anticlockwise, describes a complete process of the pyramid growth; and only every fourth step in the row (starting from the 2-ML one) results in appearance of the symmetrical cluster (the 6-ML one, 10-ML one, 14-ML one, etc). The pyramids of different heights are a little asymmetrical. This maybe means that only the symmetrical pyramids are stable while the rest are metastable.

This hypothesis would probably allow us to explain the decay of the pyramid number density and their relative fraction in the hut arrays observed during the low-temperature growth which eventually results in their virtual vanishing from the arrays at high Ge coverages.^{4,6,14}

The explanation might be as follows: Pyramids of the first stable height (2 ML) are often observed at low Ge coverages (less or around 6 Å);^{15,17} numerous 3, 4 and 5-ML pyramids are also observed at Ge coverages some less or about 6 Å (Fig. 8) when the clusters are small enough and the distances between them are large in comparison with their dimensions.¹⁴⁻¹⁷ In these conditions, if a flux of Ge atoms arriving on the surface is sufficient to feed all the growing huts and a competition between huts for Ge is actually absent, all pyramids, both stable and metastable, obtain enough material to complete their facets and grow remaining in the array. Pyramids of 6 ML high are stable but they form at greater coverages, from 6 to 8 Å, when all huts become bigger, more actively consume Ge and gaps between them become smaller.^{4,16} Only stable pyramids can survive among aggressively growing competitors, and metastable ones likely lose their substance in favor of stable counterparts (predominantly wedges), probably until decreasing in height reach 2 ML. These little pyramids are then easily overgrown by large huts. Some pyramids, probably those which nucleated at early stages and had enough time to grow, succeed to reach the stable heights of 10, 14 or 18 ML being sufficiently large to successfully compete with other clusters even at intermediate heights (between 6 and 10 ML, etc.) when they are metastable; these pyramids remain in arrays and are observed as a background with the fraction of 10 % or as array defects.^{4,6,14,15,29}

Notice also, that at high temperatures, when the cluster number density is small and the Ge dimer mobility on WL is high, pyramids become more stable than wedges which for some reason do not nucleate in the arrays.¹⁸ Pyramids can grow even being metastable at intermediate heights in these conditions as they do not experience rivalry for Ge with their counterparts.

B. Nucleation of pyramids and wedges: A scenario of a common embryo

Presently, hut nucleation poses a lot of questions, and the issue of appearance of two species of nuclei on tops of WL patches to relieve the strain,¹⁴ instead of single one which seems to be quite enough, is the most intriguing of them.^{17,18} Now, we propose a scenario which could partially explain this phenomenon by reducing the quantity of initial structures and deriving both nuclei from a common precursor (“embryo”). Fig. 9 illustrates this scenario: We suppose that each embryo consists of two rows of dimers; and each row is composed by four dimers (Fig. 9 a). Such structures are abundant on WL at low coverages (from 5 to

6 ML)¹⁵⁻¹⁸ and can be easily recognized in the STM images (Fig. 8 a; they also can be seen in the images presented in Ref. 3).

Connection of two such embryos into a whole leads to formation of a structure that has been interpreted by us as a nucleus of wedges¹⁴ (Fig. 9 b, figure 1). Then this formation can stabilize by reconstruction into the structure of the nucleus of pyramids with all bases sides aligned with $\langle 100 \rangle$ which is ready to formation of all four $\{105\}$ facets. Such structures are seen in STM images at initial phases of hut array formation at low Ge coverages (Fig. 8 a, b) and temperatures.¹⁴⁻¹⁸ A structure denoted by figure 3 in Fig. 9 b, to which the formation (1) can also transform, likely is not stable: it has only two base sides running along $\langle 100 \rangle$ and cannot form four $\{105\}$ facets. This structure is observed in STM micrographs very rarely. Probably, namely this explains the fact that height of wedge-like huts usually is greater than 2 ML. Formation of 2 ML high stable wedge-like huts likely occurs rapidly through a phase transition, which is a shift in one of the cluster parts by half translation (Fig. 9 b, transition from the state 1 to the state 3), followed by attachment, as discussed above, of specifically arranged Ge adatoms (ad-dimers) of the second monolayer.¹⁴

IV. CONCLUSION

In conclusion of the article, we would like to emphasize its main statements.

On the basis of data of recent STM investigations of nucleation and growth of Ge huts on the Si(001) surface in the process of molecular beam epitaxy, we have proposed structural models of growing Ge/Si(001) pyramids and wedges and found the huts regardless of their shapes to grow non-uniformly, expanding their bases by different number of translations in different $\langle 110 \rangle$ directions as a result of increase in their height by 1 ML, in order to conserve the dimer arrangement on their apexes, as observed experimentally. We have concluded from the model of non-uniform growth that growing pyramids, starting from the second terrace, increase their heights via cyclic (recurrent) formation of slightly asymmetrical and symmetrical shapes, with symmetrical ones appearing after addition of every fourth (001) terrace. We suppose that only symmetrical configurations of pyramids composed by 2, 6, 10, 14, etc. terraces over WL are stable. This might explain less stability of pyramids in comparison with wedges in dense arrays obtained at low Ge deposition temperatures.

We have proposed and discussed possible processes of nucleation of pyramids and wedges

on WL patches from the same embryos composed by 8 dimers grouped in two rows through formation of 1 ML high 16-dimer nuclei different only in the symmetry of arrangement of their dimers. The proposed models, which consider the very beginning of formation of Stransky-Krastanov Ge/Si(001) clusters on atomic level, seem to show the way on which the issue of simultaneous nucleation, with equal likelihoods, of two species of huts at low temperatures of Ge deposition can be solved.

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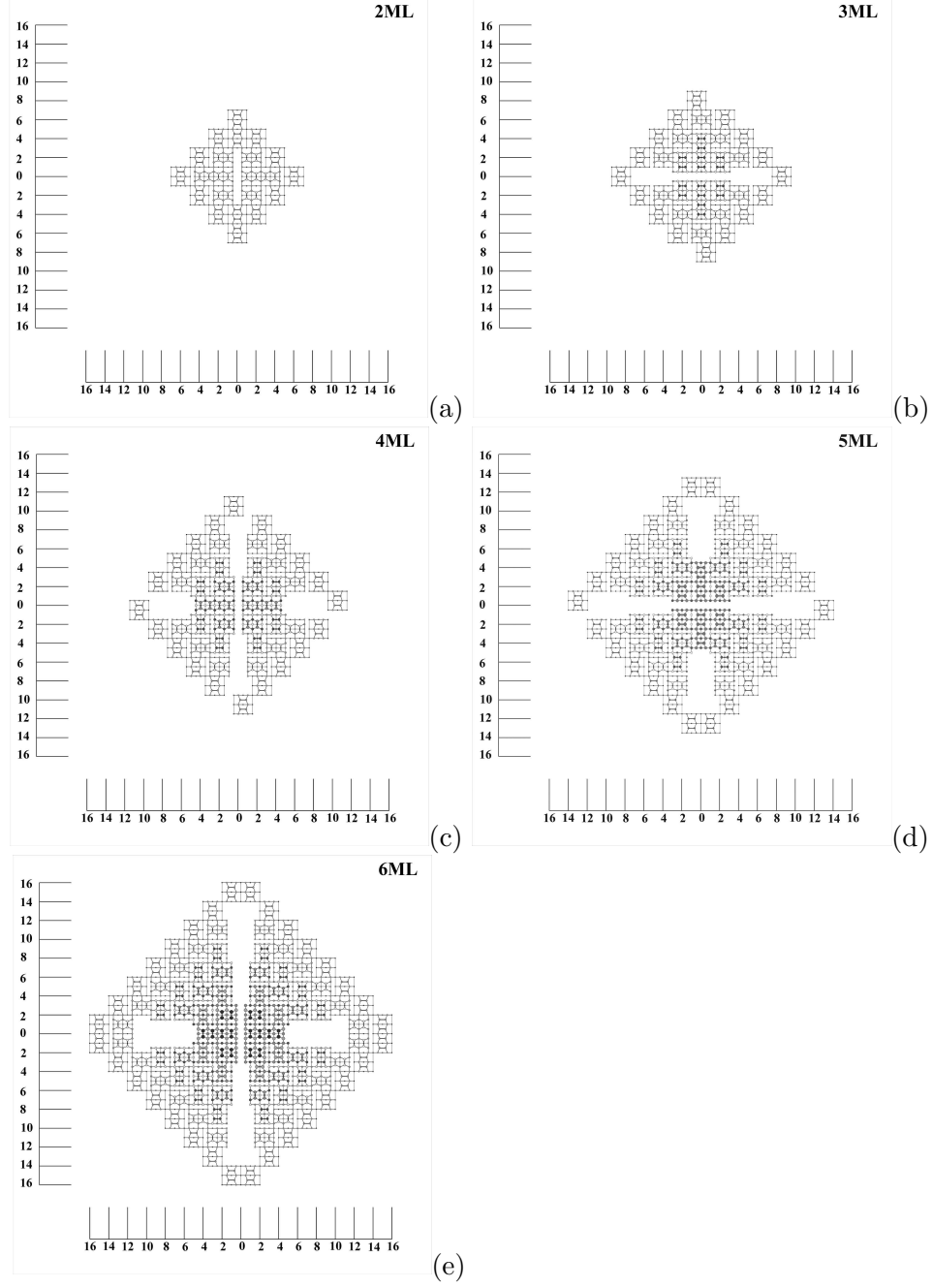


FIG. 6. A model of non-uniform growth of a pyramidal hut: the cluster height over WL is 2 (a), 3 (b), 4 (c), 5 (d) and 6 (e) ML. Only the structures of the $\{105\}$ facets and the blossom-like apices are shown. The axes represent the cluster base half-widths along the $\langle 110 \rangle$ axes expressed in units of elementary translations. The drawings are centered at the (00) point.

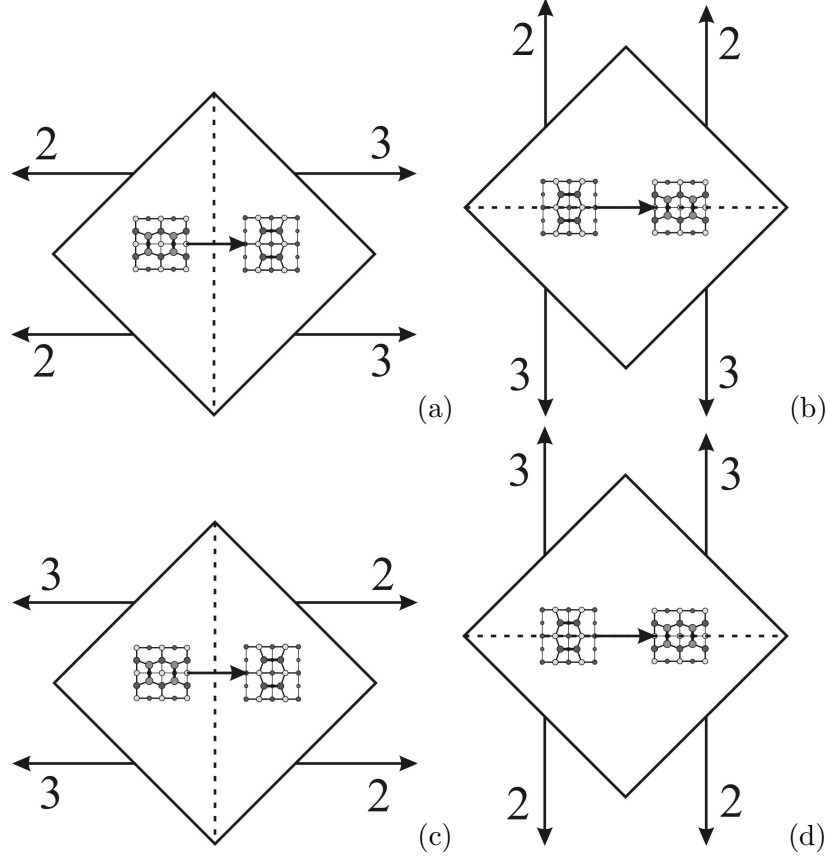


FIG. 7. Schematic representation of a cycle of the non-uniform growth of a pyramidal hut-cluster depending on the initial and final direction of dimer rows on its apex. Each panel correspond to pyramid growth by 1 ML, e.g., to the transitions between growth phases from 2 to 6 ML shown in Fig. 6: 2 ML to 3 ML (a), 3 ML to 4 ML (b), 4 ML to 5 ML (c), 5 ML to 6 ML (d) (or in the same order of steps from 6 to 10 ML, from 10 to 14 ML and so on). The apex rotation is shown by sketches of the unit cells connected by arrows inside the squares; the arrowheads show the final directions which are vertical in panels (a), (c) and horizontal in panel (b) (d). Arrows at bases show the $\langle 110 \rangle$ directions and figures near them display a number of elementary translations to which the corresponding base side is shifted in the indicated direction due to the increase in the cluster height by 1 ML.

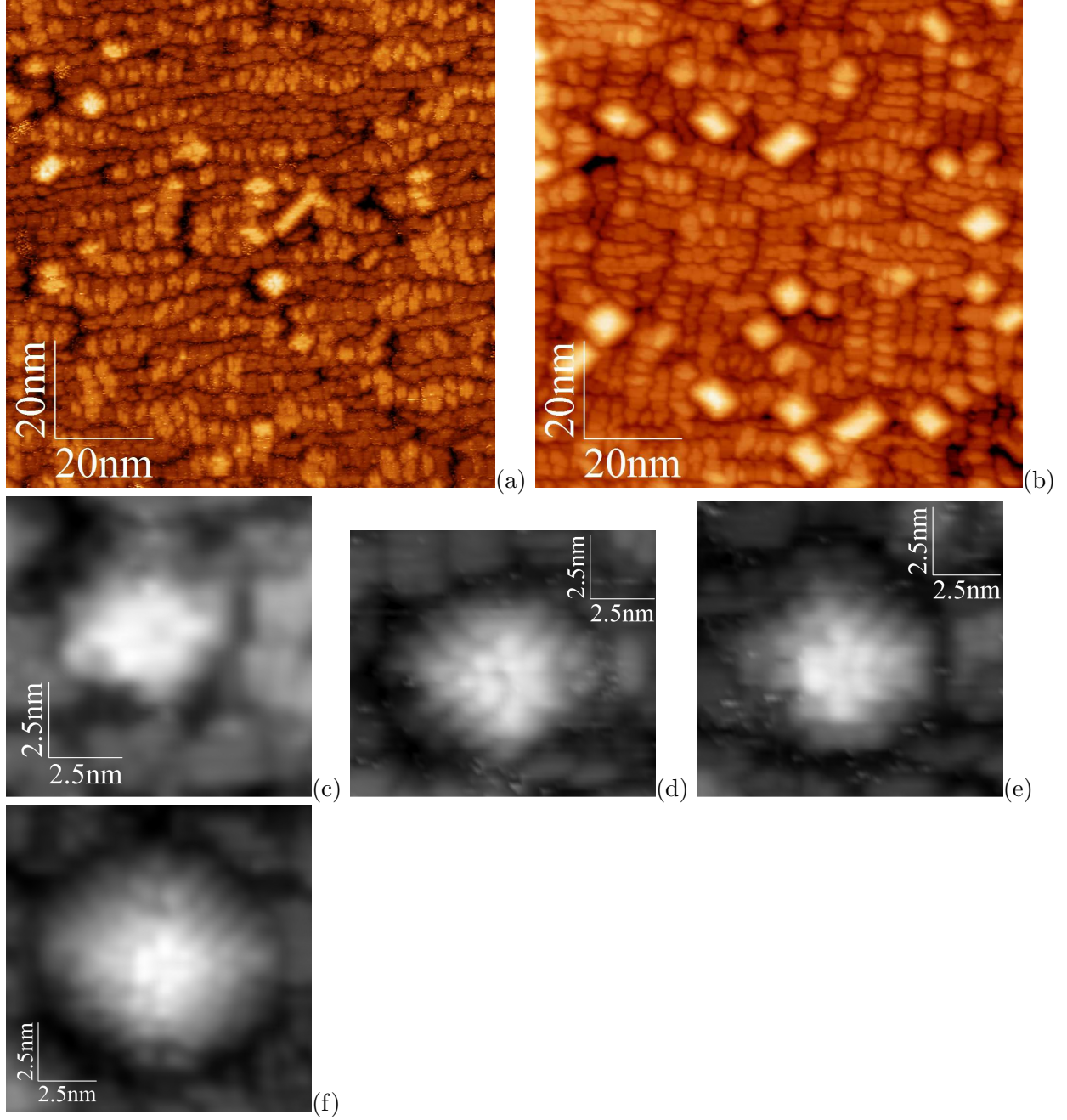


FIG. 8. (Color online) STM empty-state images of Ge hut arrays (a),(b) and pyramids (c),(d),(e),(f) grown at 360°C: 2, 3, 4 and 5-ML pyramids are seen in a variety among wedge-like huts in panels (a) and (b); micrographs of 2 (c), 3 (d),(e) and 5 ML (f) high (over WL) pyramids demonstrate fine details corresponding with the diagrams presented in Fig. 6; the Ge coverage is 5.4 Å in panels (a), (c), (d) and (e) and 6 Å in (b) and (f); bias voltage and tunneling current are +1.8 V and 100 pA in panels (a), (c), (d) and (e), +2 V and 100 pA in (b), and +2.6 V and 80 pA in (f).

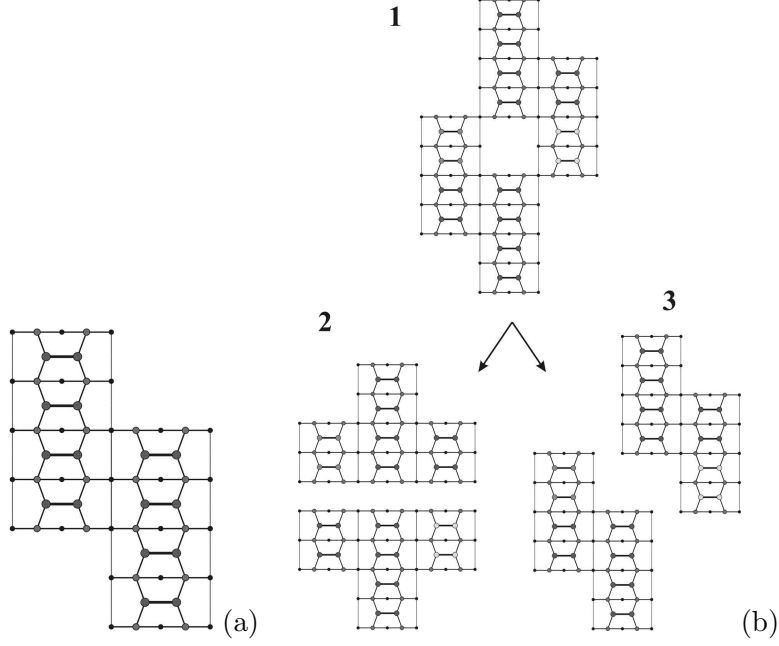


FIG. 9. Schematics of hypothetical processes of pyramidal and wedge-like hut nuclei formation from a single embryo: the embryos, like that shown in panel (a), form the nuclei (b) by pairing into a 16-dimer formation (1) followed by reconstruction into the blossom-like nucleus of a pyramid (2) or into the structure (3) preceding the formation of the wedge unit presented in Fig. 2 d.